Precision studies for CVC tests

- physics of $0^+ \rightarrow 0^+$ β transitions
- recent experimental efforts
- world data on $0^+ \rightarrow 0^+$ decay
- present future studies

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BRIX meeting, Mol, 7-8 may 2008

Standard model of weak interaction

- SM is theory which describes electro-weak interaction
- BUT: parameters have to be determined experimentally
  e.g. masses, coupling constants, mixing angles, etc.
- nuclear β decay is weak process and may allow the determination of these parameters
- 5 different couplings possible due to Lorentz invariance:
  - scalar coupling (S)
  - vector coupling (V)
  - tensor coupling (T)
  - axial-vector coupling (A)
  - pseudo-scalar coupling (P)
- β decay: mainly vector and axial-vector ➔ V-A theory
- weak contribution from other coupling?? ➔ scalar, tensor coupling
- determination of vector coupling constant: $0^+ \rightarrow 0^+$, n decay, π decay
- determination of axial-vector coupling constant: neutron decay

Beta decay and coupling constants

- in general:

$$ft = \frac{K}{g_V^2 \langle M_F \rangle^2 + g_A^2 \langle M_{GT} \rangle^2}$$

- for $0^+ \rightarrow 0^+$ transitions: only vector current due to selection rules

$$ft = \frac{K}{g_V^2 \langle M_F \rangle^2} = f(Q_{ec}) * T_{1/2} / BR$$

- experimental quantities:
  masses of parent and daughter, half-life, branching ratio

- $K / (\hbar c)^6 = 8120.271(12) * 10^{-10}$ GeV^{-4} s = constant, $\langle M_F \rangle^2 = T(T+1) - T_{zi} T_{zf}$

- $g_v = g_F * V_{ud}$ to be determined

- one high-precision measurement would be enough

- BUT…..

Corrections, CVC, CKM matrix

- electromagnetic interactions: e.g. positron with protons

  → radiative correction $\delta_R \rightarrow \delta_R', \Delta_R$

- isospin impurity: binding energy difference, configuration mixing

  → Coulomb correction $\delta_c = \delta_{c1} + \delta_{c2} \rightarrow \delta_c + \delta_{NS}$

- if these effects corrected: constant *ft* value

  → constant vector current hypothesis (CVC)

  → $$Ft = ft\,(1 + \delta_R')\,(1 - \delta_c + \delta_{NS}) = \frac{K}{g_V^2\,(1 + \Delta_R)\,\langle M_F \rangle^2}$$

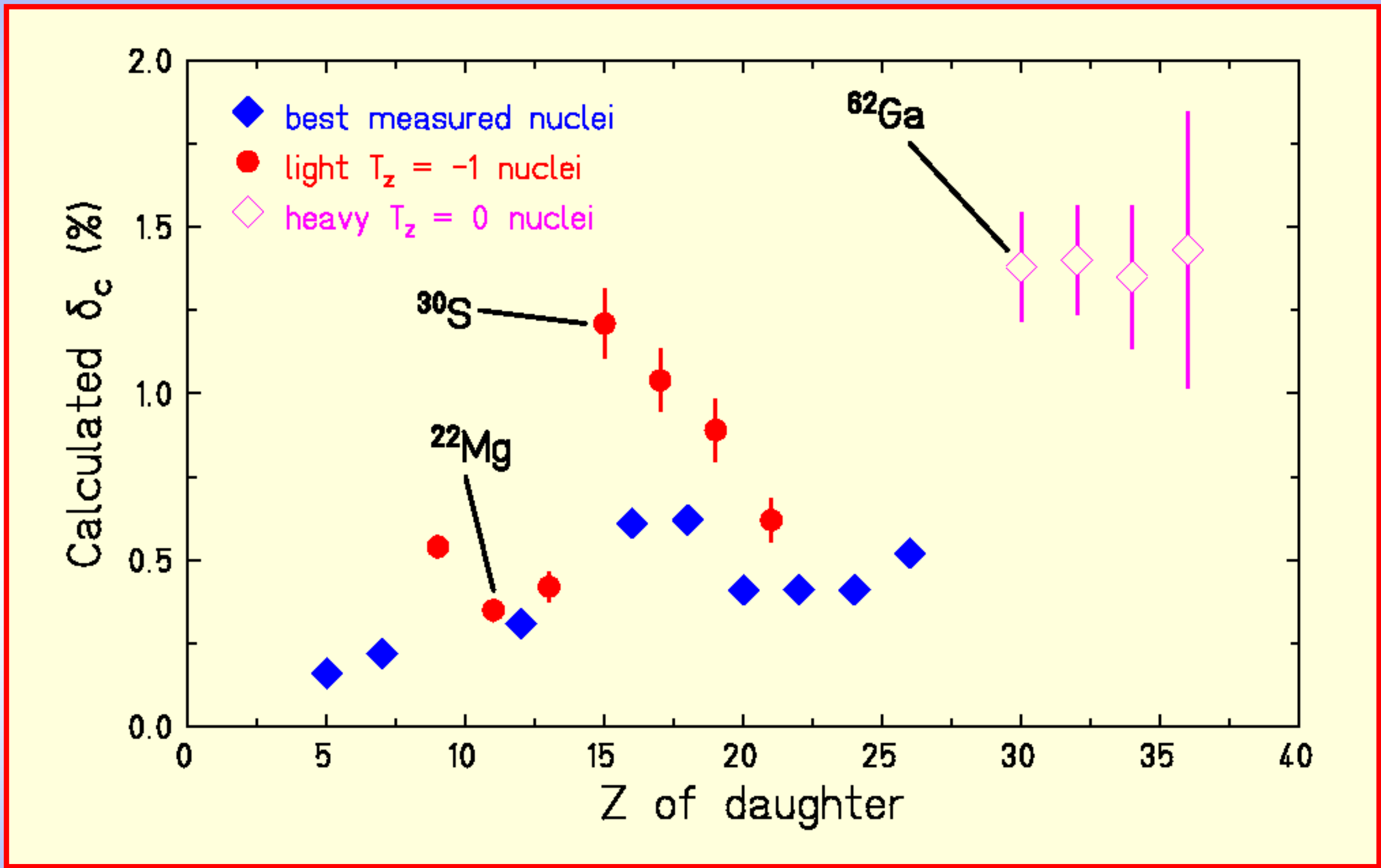
- determination of g_v via Ft value:

  → many *ft* values are needed to test CVC and theoretical corrections

- from g_v:

  → determination of V_{ud} matrix element of CKM quark mixing matrix
  $V_{ud} = g_v / g_F$

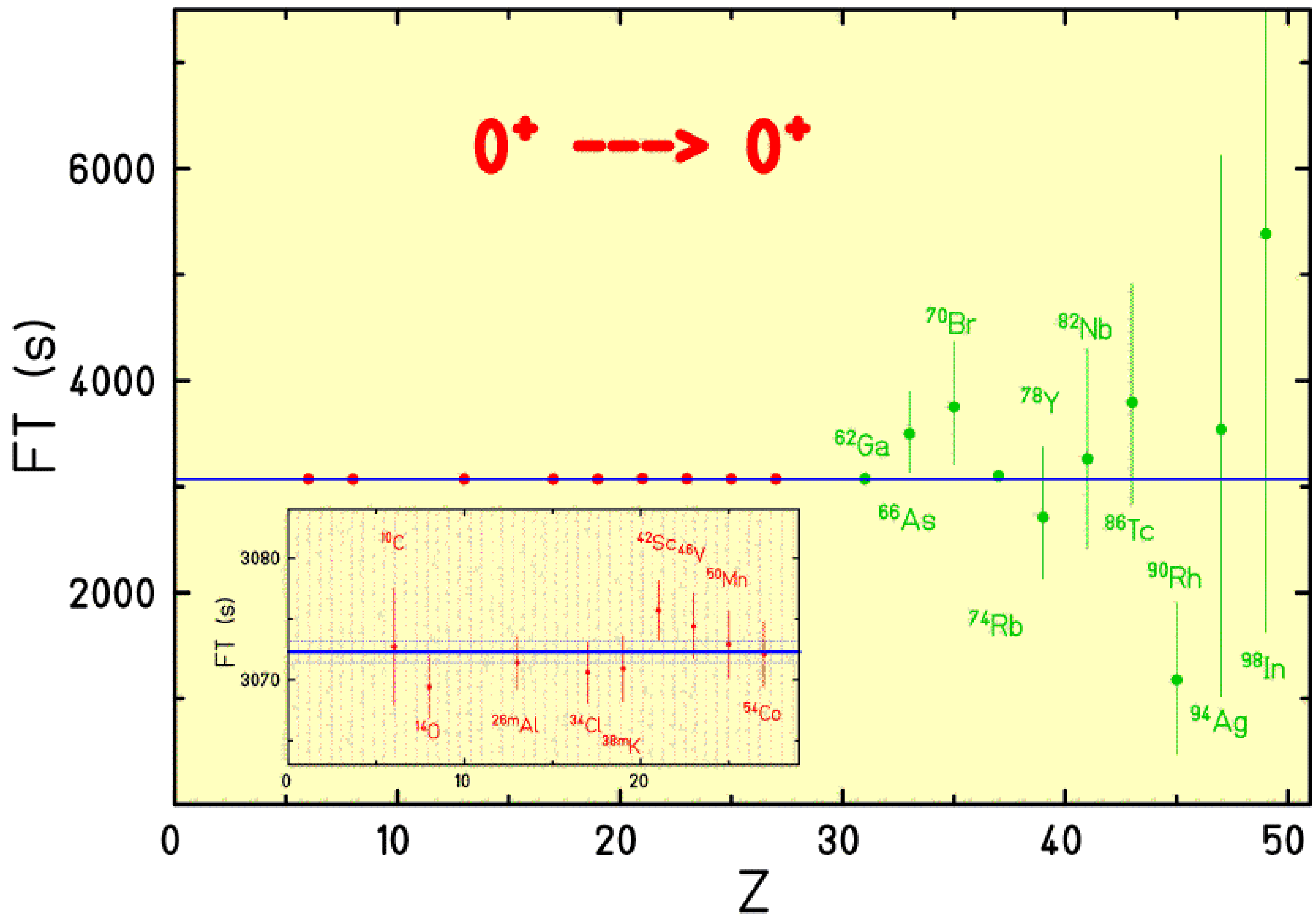
isospin-mixing corrections



Towner & Hardy, 2005, 2007

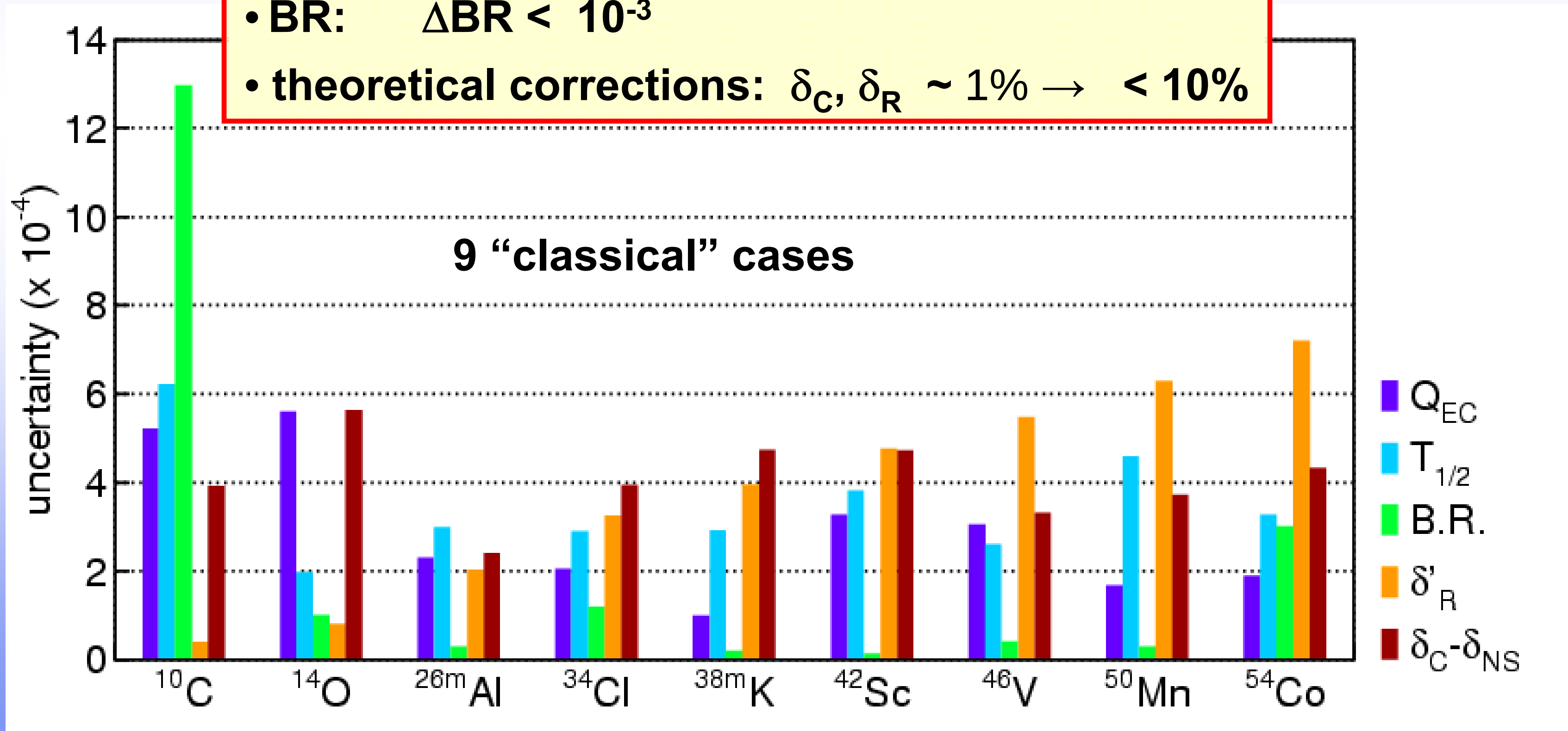
Close to ^{100}Sn, error bars should become smaller…

Situation in 2000



Required precision

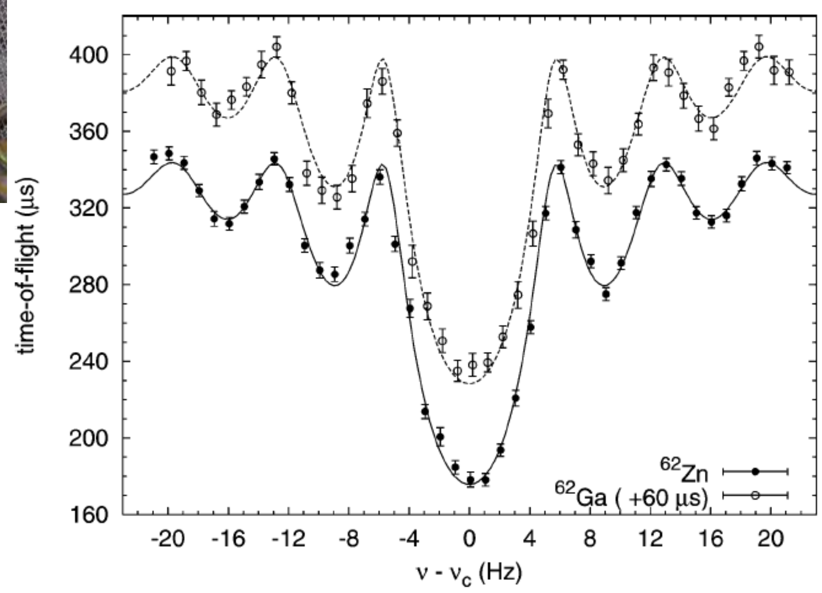
- overall precision: Ft = (3073.5 ± 1.2) s
  - ⇒ $4 * 10^{-4}$
  - ⇒ single measurements: 10^{-3}
- f: $f(Q_{EC}^{5})$ → $\Delta Q < 2 * 10^{-8}$ → < 1keV
- $T_{1/2}$: $\Delta T < 10^{-3}$
- BR: $\Delta BR < 10^{-3}$
- theoretical corrections: δ_C, δ_R ~ 1% → < 10%



Our recent efforts: Q value of Ga-62

- **Q value measurements at JYFLTRAP: ^{62}Ga**

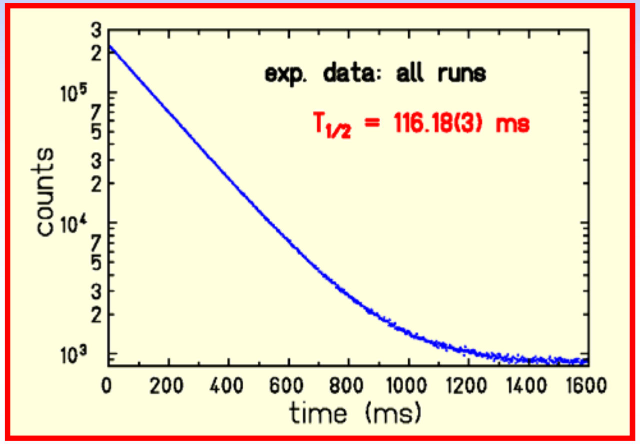
$Q_{EC} = (9181.07 \pm 0.54)$ keV

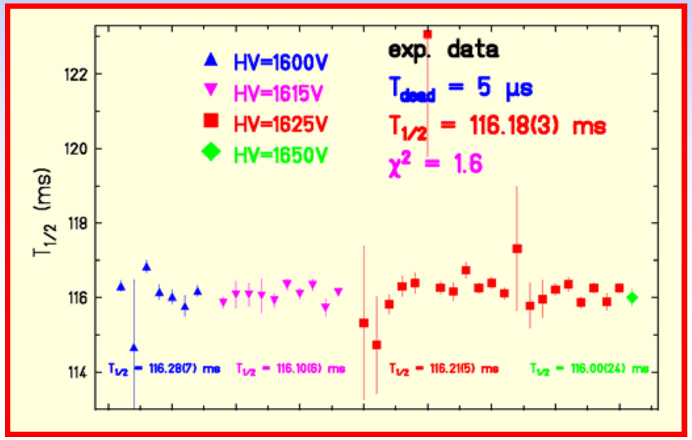


T. Eronen et al., 2006

Our recent efforts: half-life of Ga-62

- **half-life measurement at GSI:**

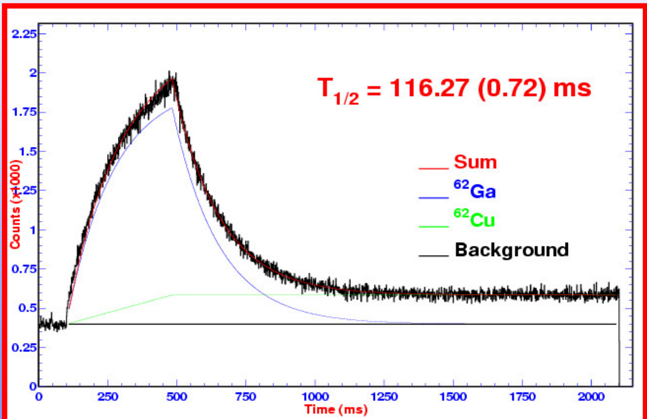


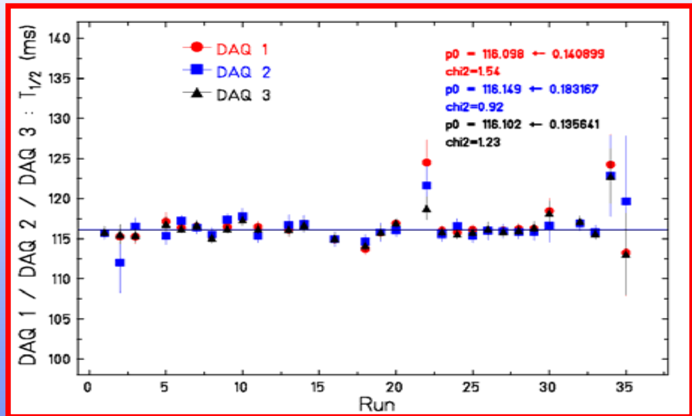


$T_{1/2}$ = (116.18 ± 0.04) ms

B. Blank et al., 2004

- **half-life measurement at JYFL:**



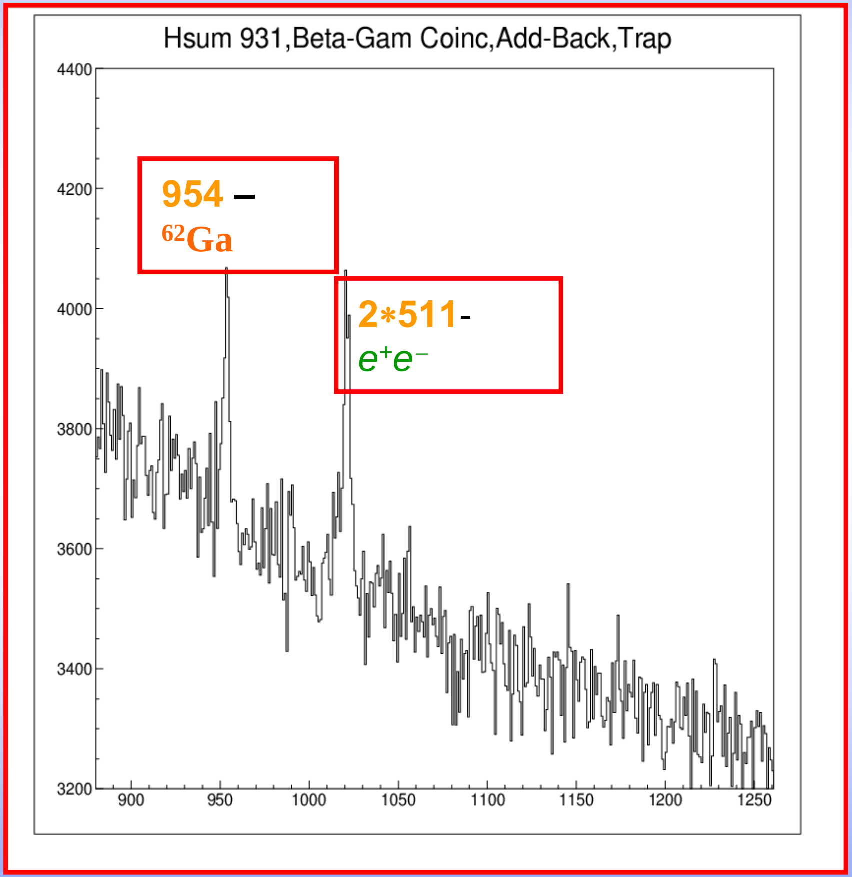


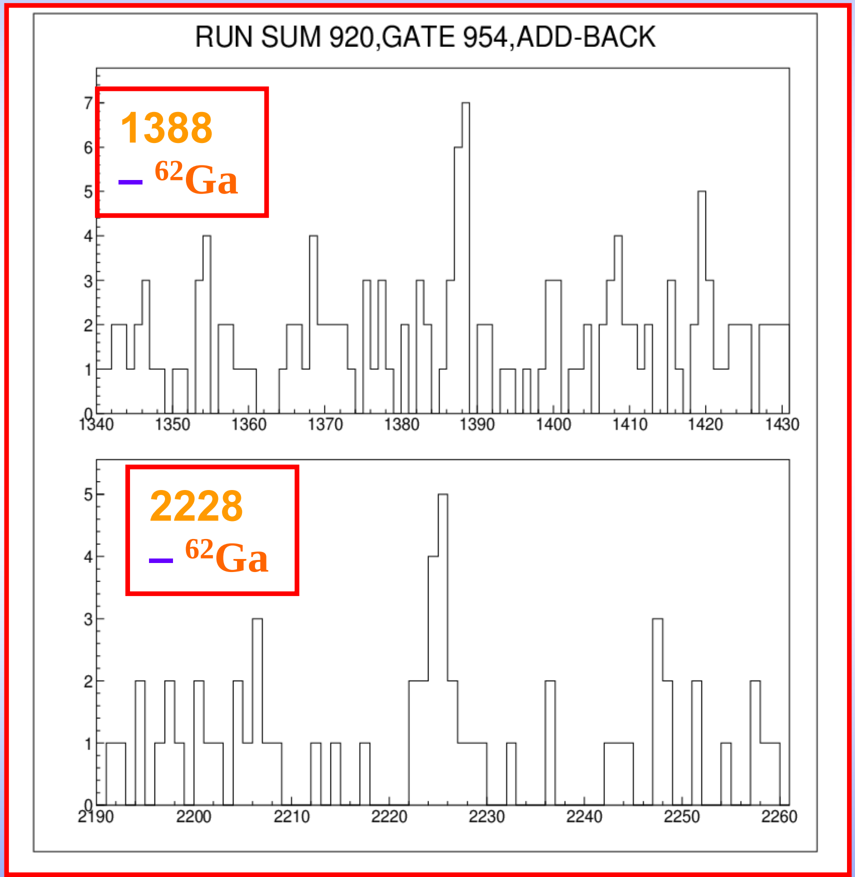
$T_{1/2}$ = (116.12 ± 0.15) ms

G. Canchel et al., 2005

Our recent efforts: branching ratio of Ga-62

• **branching ratio measurement at JYFL:**



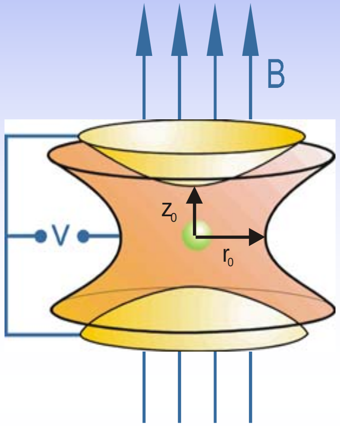


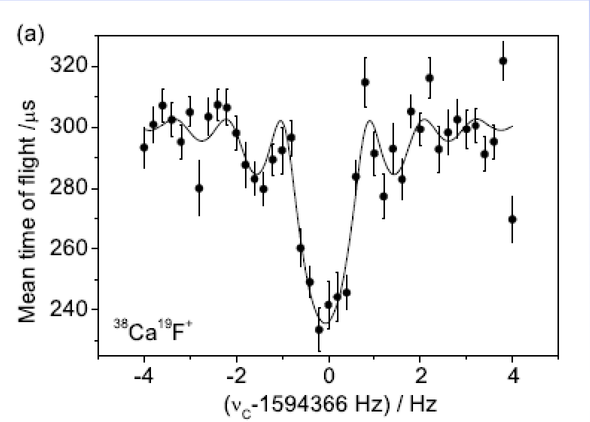
BR = (99.905 ± 0.026) %

A. Bey et al., 2008

Our recent efforts: Q value and half-life of Ca-38

• **Q value measurements at ISOLTRAP: e.g. ^{38}Ca**

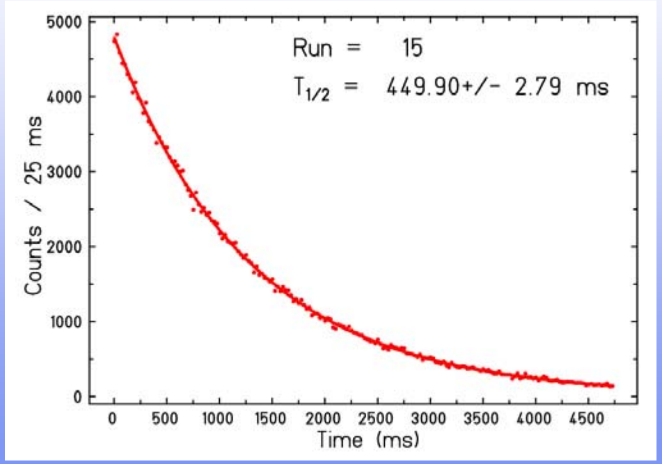


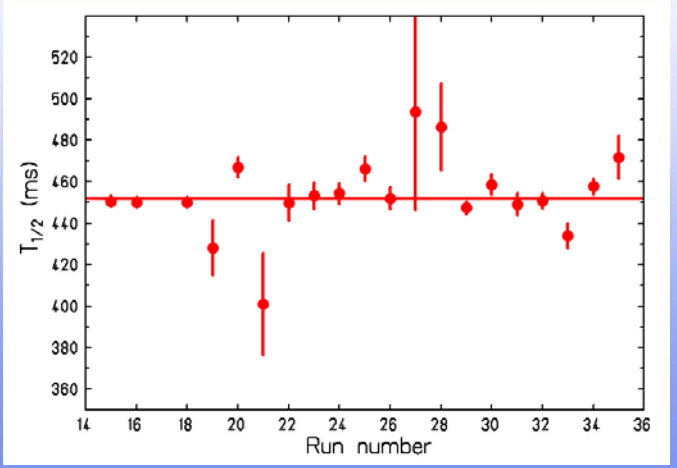


Δm = (-22058.01±0.65) keV

S. George et al., 2007

• **half-life measurements at ISOLDE / REXtrap : e.g. ^{38}Ca**

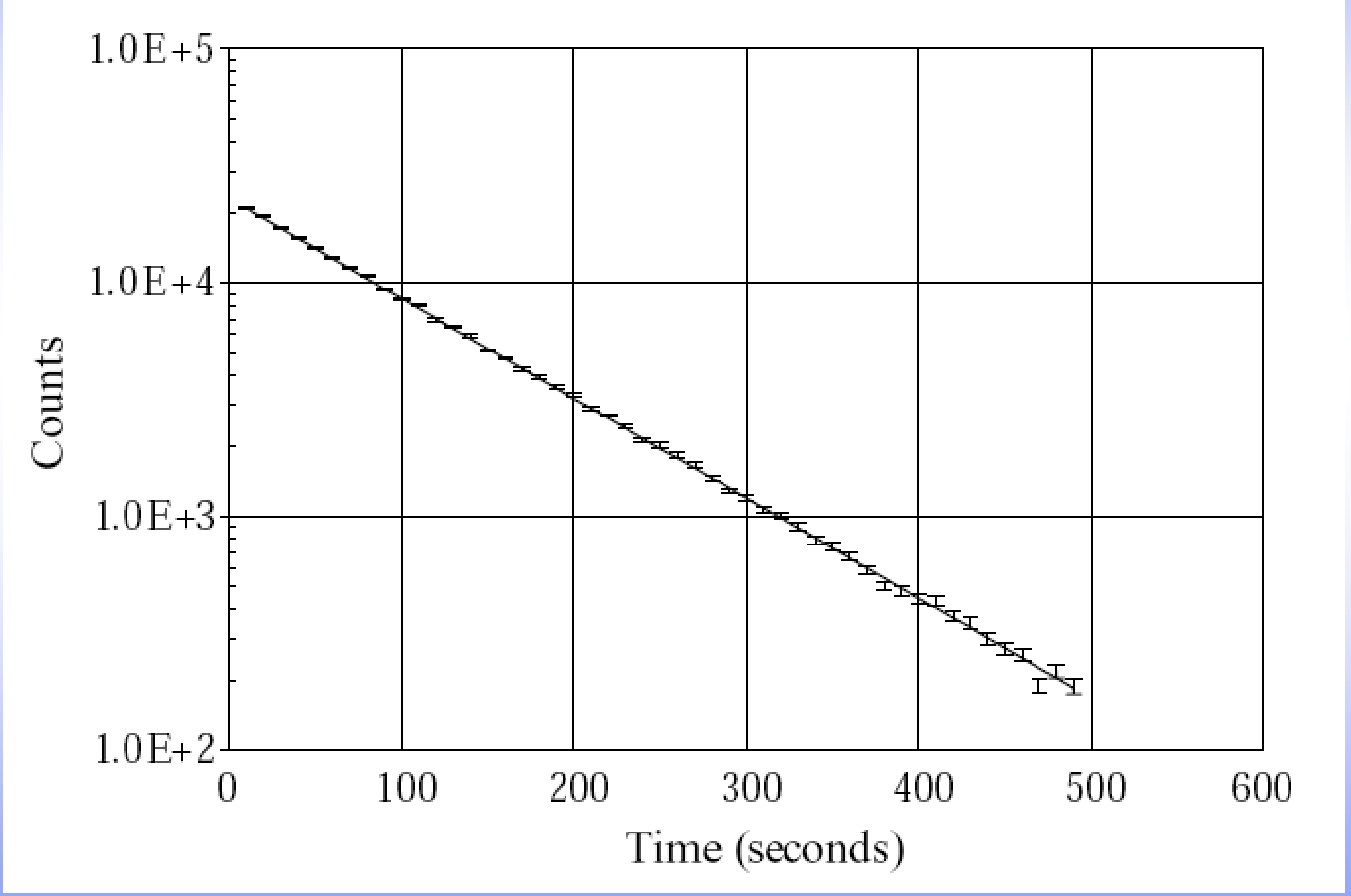




I. Matea et al.

Recent experimental efforts: LEUVEN

• **half-life measurement: ^{14}O**



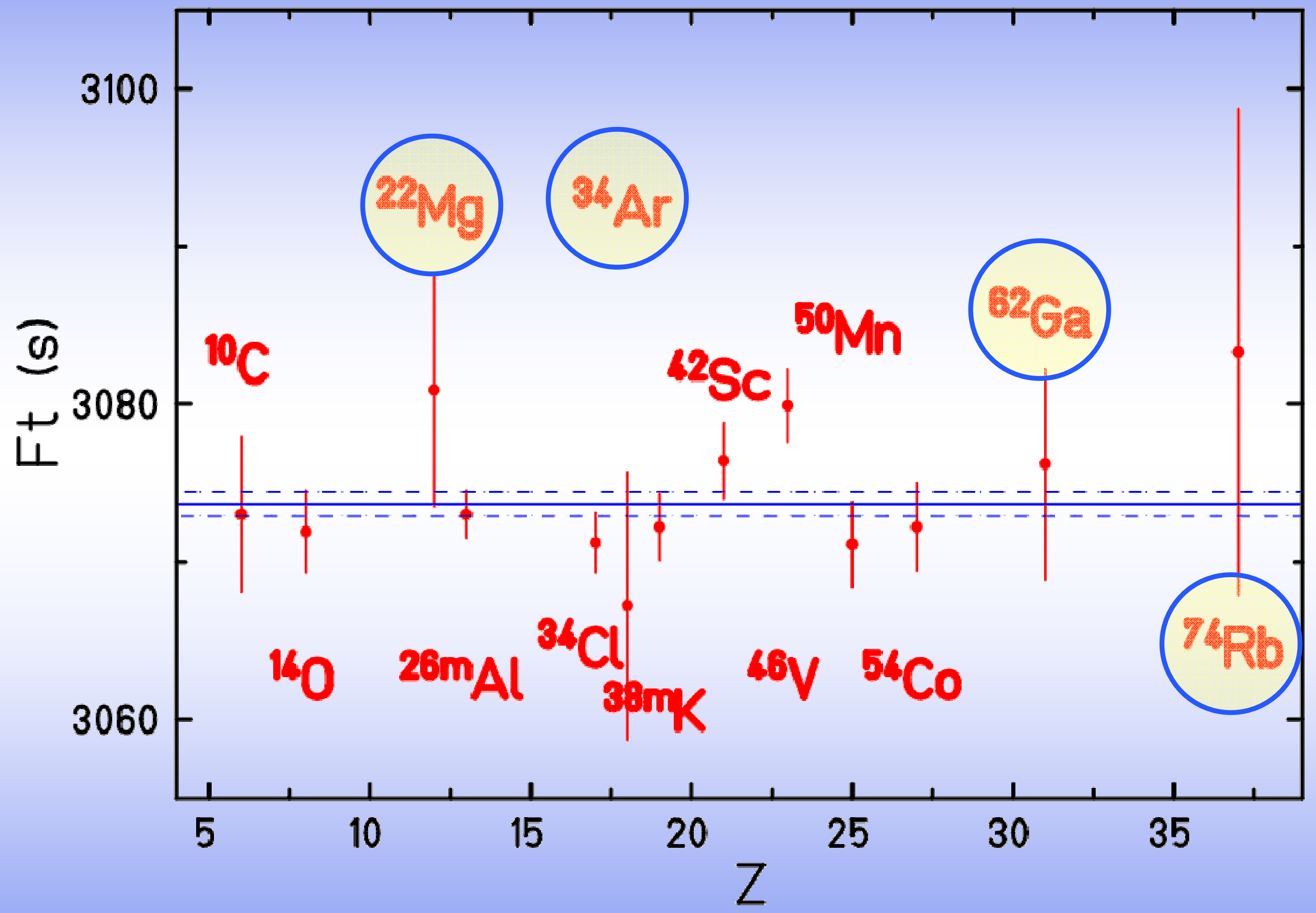
$T_{1/2} = (70.560 \pm 0.049)$ s

M. Gaelens et al., 2001

Experimental results after 2000

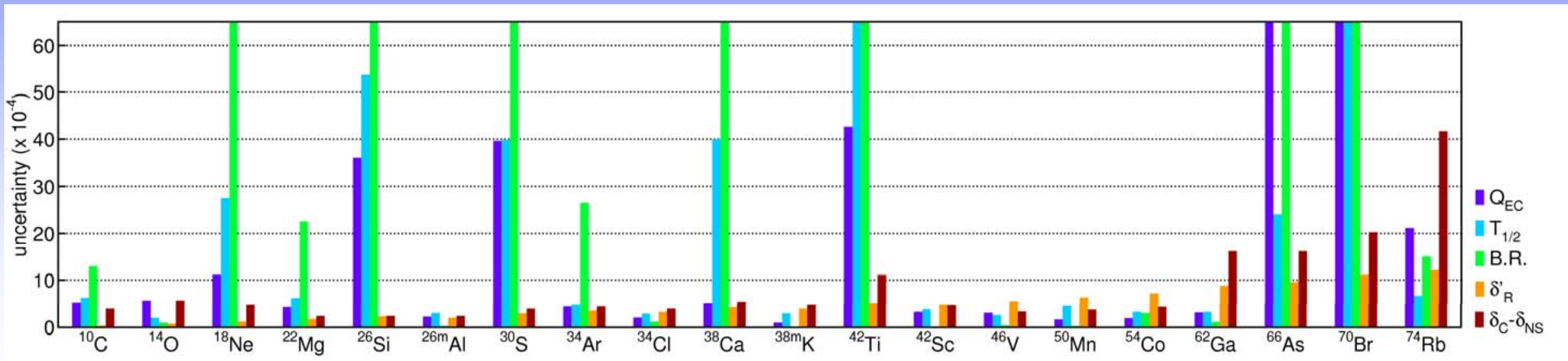
^{10}C	T1/2	Texas A&M
^{14}O	$T_{1/2}$	Leuven, Auckland, Berkeley
	Q_{EC}	Auckland
^{18}Ne	$T_{1/2}$	TRIUMF
	Q_{EC}	ISOLDE
^{22}Mg	$T_{1/2}$, BR	Texas A&M
	Q_{EC}	CPT Argonne, ISOLDE
^{26}Si	$Q_{EC,}$ $T_{1/2}$	JYFL
$^{26}Al^{m}$	Q_{EC}	JYFL
^{34}Ar	$T_{1/2}$, BR	Texas A&M
	Q_{EC}	ISOLDE
^{38}Ca	Q_{EC}, T_{12}	ISOLDE, Texas A&M
	Q_{EC}	MSU
$^{38}K^{m}$	$T_{1/2}$	Auckland
^{42}Sc	Q_{EC}	JYFL
^{42}Ti	Q_{EC}	JYFL
^{46}V	Q_{EC}	JYFL, CPT Argonne
^{50}Mn	Q_{EC}	JYFL
	$T_{1/2}$	Auckland
^{54}Co	Q_{EC}	JYFL
^{62}Ga	$T_{1/2}$, BR	GSI, JYFL, TRIUMF, Texas A&M
	Q_{EC}	JYFL
^{74}Rb	$T_{1/2}$,BR	TRIUMF, ISOLDE
	Q_{EC}	ISOLDE

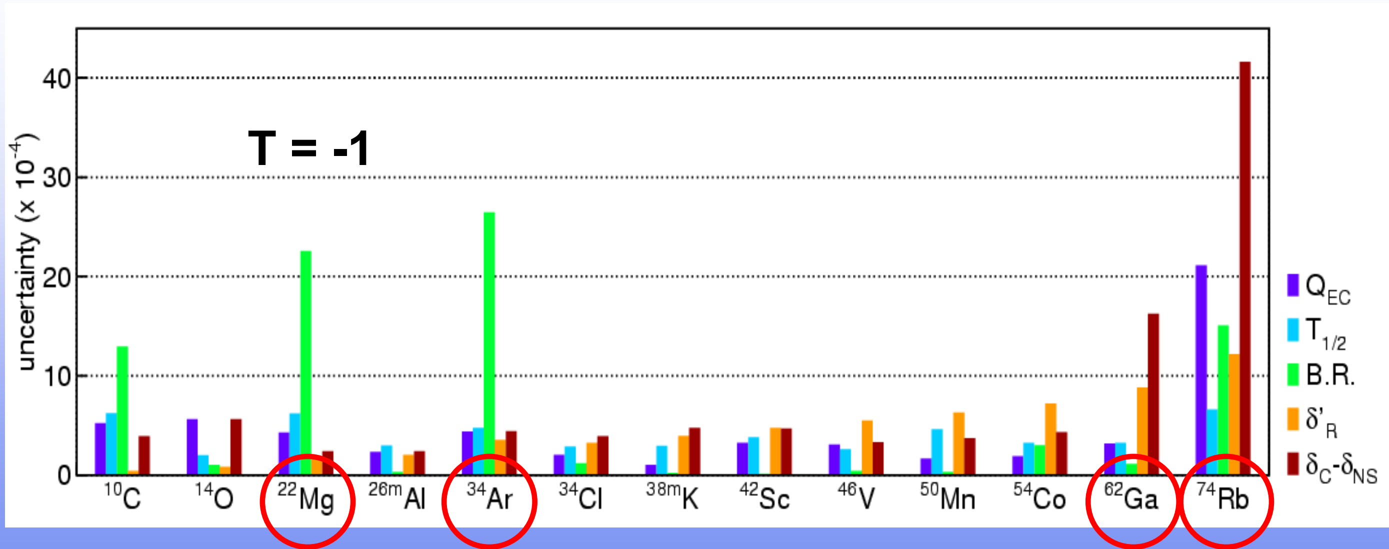
Summary of experimental and theoretical results



<Ft> = (3074.4 ± 1.2) s $\Rightarrow$ g_V = 1.1358(4) $\Rightarrow$ V_{ud} = 0.9736(4)

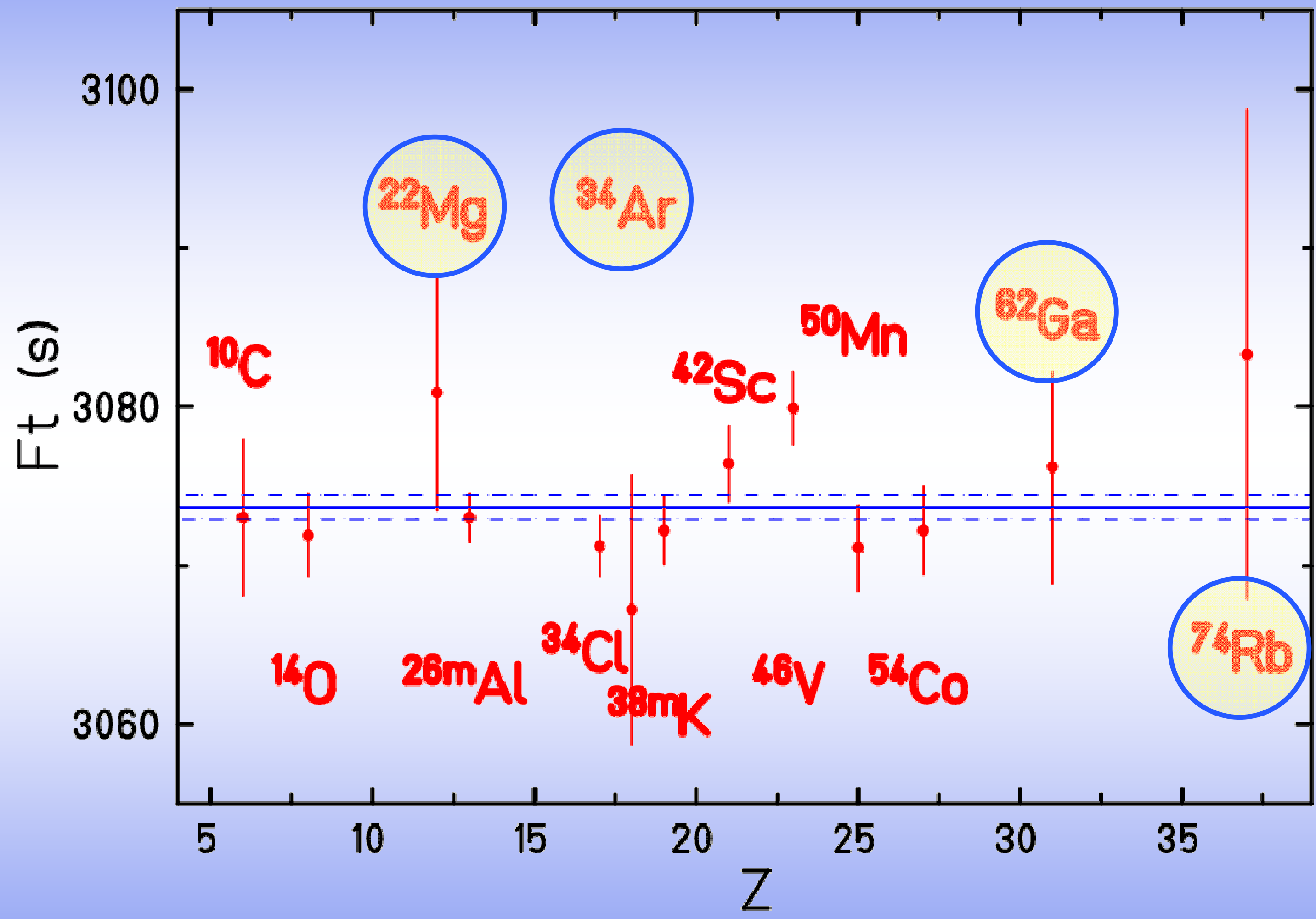
Error budget





- **CVC accepted**
- **measurement of ft**
- **$\delta_c + \delta_{NS}$ determined**
- **test of theoretical models**

Summary of experimental and theoretical results



$\langle Ft \rangle = (3074.4 \pm 1.2)$ s $\Rightarrow g_V = 1.1358(4) \Rightarrow V_{ud} = 0.9736(4)$

CKM quark mixing matrix

• *coupling of quark weak eigen states to mass eigen states in the Standard Model*

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

➔ ***unitarity condition:***

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

V_{ud} = 0.9736(4) ~ 95 %
V_{us} = 0.2254(21) ~ 5 %
V_{ub} = 0.00367(47) ~ 0 %

• *the situation today*

➔ $\sum V_{ui}^2 = 0.9987(12)$

V_{ud} — $0^+ \rightarrow 0^+$ β decays: 0.9736(4)
neutron decay: 0.9741(20)
➪ Part. Data Group (2004)
(Serebrov et al. (2005) not included)
pion beta decay: 0.9728(30)
➪ larger uncertainty

V_{us} — K_X decays + form factor
➪ Leutwyler-Roos (1984)
➪ Cirigliano et al. (2005)

deviation to unitarity		V_{ud} nuclear $0^+ \rightarrow 0^+$	V_{ud} neutron pdg 04	V_{ud} neutron Se 05
V_{us}	K decay: pdg04	~ 2σ	~ 2σ	ok
V_{us}	K: all results	~ 1σ	ok	~ 2σ

Severijns, Beck, Naviliat-Cuncic, 2006

The standard model and beyond

- *limit on induced scalar currents:*

  $f_s = -0.00005(130)$ or $|fs| \leq 0.0013$

- *limit for fundamental scalar current:*

  $|Cs / Cv| \leq 0.0013$

- *limit for Fierz interference term:*

  $b_F = 0.0001(26)$

  $$Ft = \frac{K}{2\, G_F^2\, V_{ud}^2\, (1 + \Delta^V_R)} \; \frac{1}{(1 + \langle b'_F \rangle)}$$

- *limits on right-handed currents:*

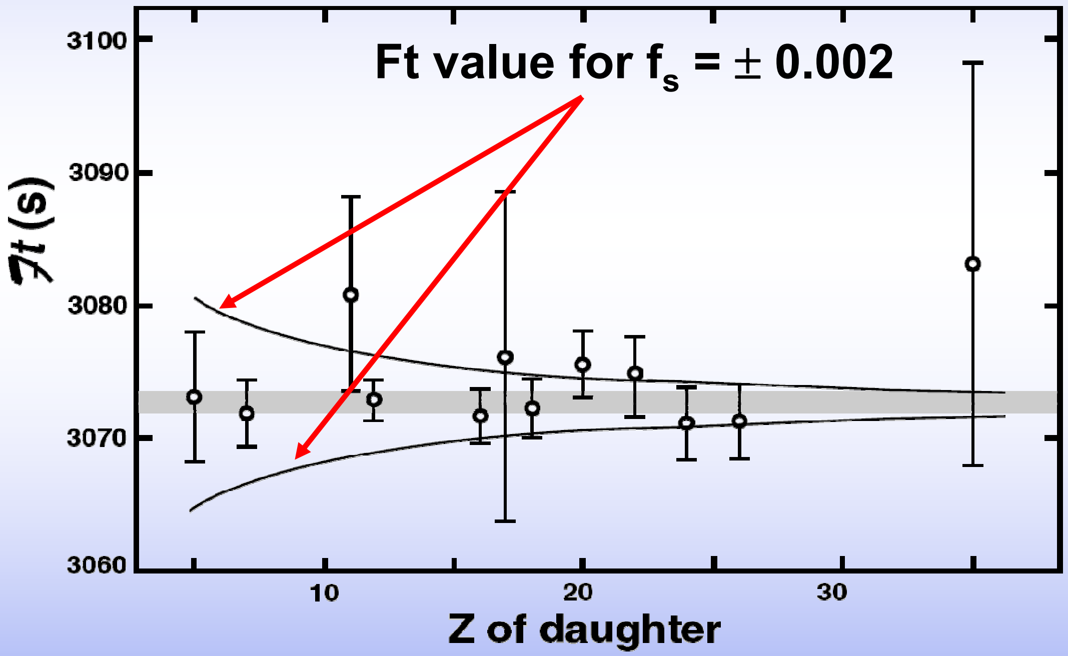
  $-0.0005 < \zeta < 0.0015$ (90% C.L.)

  $W_1 = W_L \cos\zeta - W_R \sin\zeta$
  $W_2 = W_L \sin\zeta + W_R \cos\zeta$

- *unitarity of first column of CKM matrix:*

  $\sum V_{id} = 0.9985(54)$

➔ *best limits from all approaches*



Hardy & Towner, 2005

Improvements between 1990 and 2005

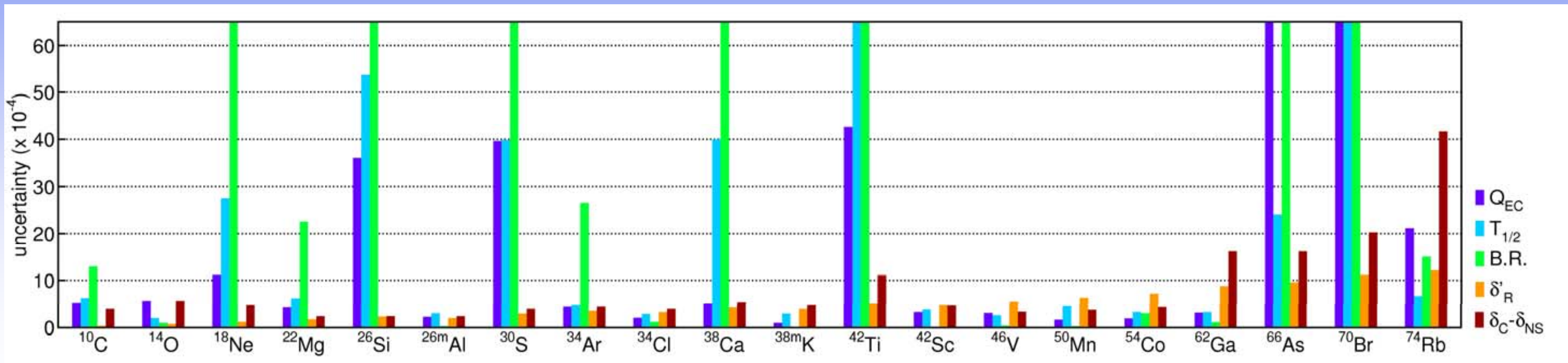
- uncertainty on <Ft> :
  3073.3(35) s → 3074.4(12) s ==>> 30 % due to more and more precise exp. data
- Fierz term :
  0.0010(30) → 0.0001(26) ==>> strongly reduced value due to better exp. data
- V_{ud} :
  0.9740(10) → 0.9736(4) ==>> slight change, factor 2.5
- unitarity test of first row of CKM matrix:
  $\sum V_{ui}$ = 0.9970(21) → $\sum V_{ui}$ = 0.9987(12) ==>> change mainly due to V_{us}, improved precision from Ft
- unitarity test of first column of CKM matrix:
  → $\sum V_{id}$ = 0.9985(54) ==>> not evaluated in 1990
- right-handed currents:
  → $Re(a_{lr})$ = -0.0004(6) ==>> not evaluated in 1990

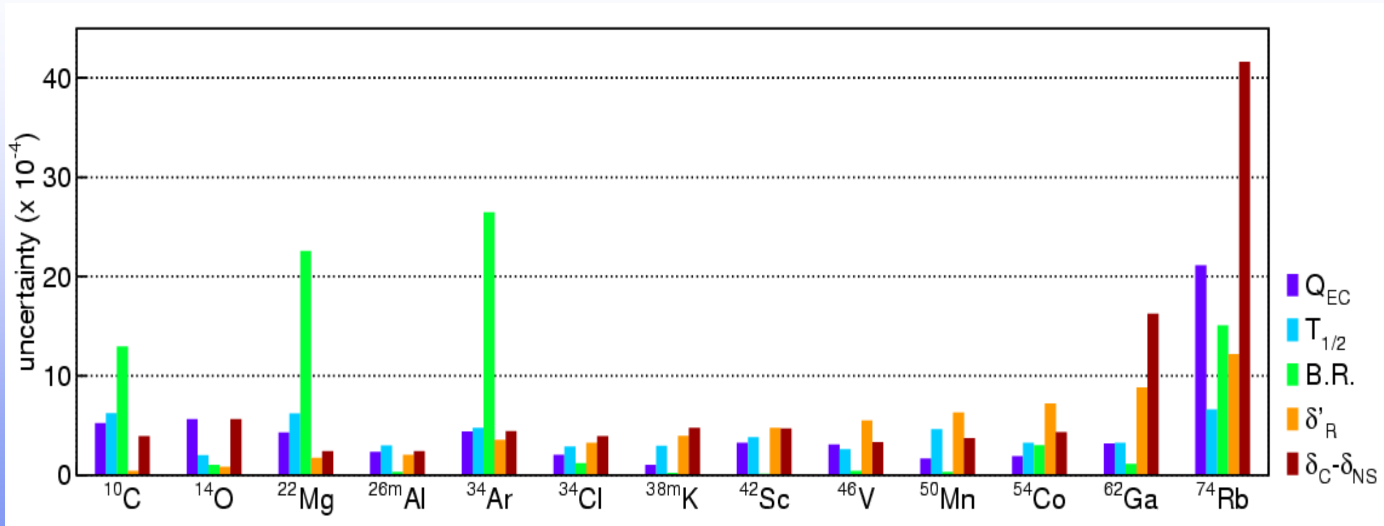
Hardy & Towner

Present efforts

- T_z = -1 nuclei: ^{10}C, ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, ^{38}Ca, ^{42}Ti
  - major problems:
    - $T_{1/2}$ of daughter nuclei
    - BR with precision of 10^{-3} → absolute γ efficiency with < 10^{-3}
      → knowledge of source strength
  - solutions:
    - trap-assisted spectroscopy for half-life measurements
    - high-precision efficiency calibration of single-crystal Germanium
    - ion counting → experiments on separators like MARS (Texas A&M), LISE3 (GANIL), TRμMP (KVI)
- T_z = 0 nuclei: ^{42}Sc, ^{46}V, ^{50}Mn, ^{54}Co, ^{62}Ga, …
  - major problem:
    - Q value from reactions, production rates
  - solution:
    - Penning traps
- theoretical corrections:
  - new approaches needed for nuclear corrections
  - higher-order calculations for QED corrections

Error budget





- **CVC accepted**
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Future efforts

MYRRHA

- $T_z = 0$ nuclei: ^{66}As, ^{70}Br, ^{78}Y, ^{82}Nb, ^{86}Tc, …^{98}In
  - major problem:
    production rates, for some isomers
  - solution:
    future facilities with much higher intensities or longer beam times

- $T_z = -1$ nuclei: beyond ^{42}Ti …. ^{98}Sn
  - major problems:
    production rates
    BR with precision of 10^{-3} → absolute γ efficiency with < 10^{-3}
    → knowledge of source strength
  - solutions:
    new facilities, long beam times

- $T_z = -2$ nuclei: ^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ^{36}Ca, ^{40}Ti, ^{46}Cr, ^{50}Fe, ^{54}Ni
  - major problems:
    production rates, proton emission !!
    BR with precision of 10^{-3} for p and γ emission
  - solutions:
    new facilities, long beam times

Nuclei of interest

- ^{66}As, ^{70}Br, ^{74}Rb, ^{78}Y, ^{82}Nb, ^{86}Tc, ^{90}Rh, ^{94}Ag, ^{98}In

- source types (from ISOLDE web page):

- hot plasma:	^{66}As, ^{78}Y, ^{94}Ag, ^{98}In
- neg. surface ionisation:	^{70}Br
- surface ionisation:	^{74}Rb, ^{78}Y (+CF_4), ^{94}Ag, ^{98}In
- no ISOL elements:	^{82}Nb, ^{86}Tc

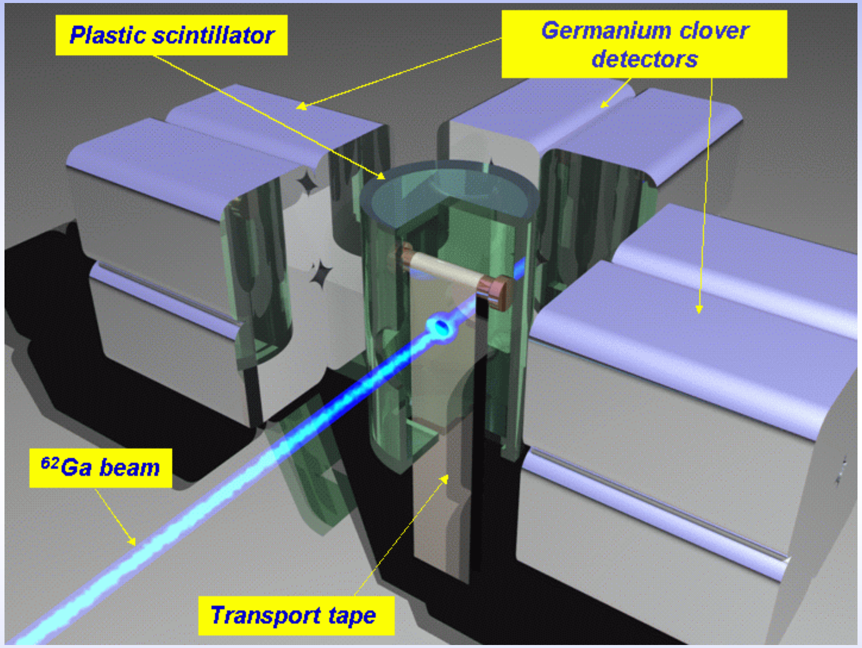
- measurements to be performed: Q_{EC}, $T_{1/2}$, BR

  Q_{EC}: Penning traps
  $T_{1/2}$: Gas detectors or plastic scintillators
  BR: Germanium detectors (+ β detector for normalisation)

Setups needed

Q_{EC} value: Traps

T1/2 and BR: β and Ge detectors



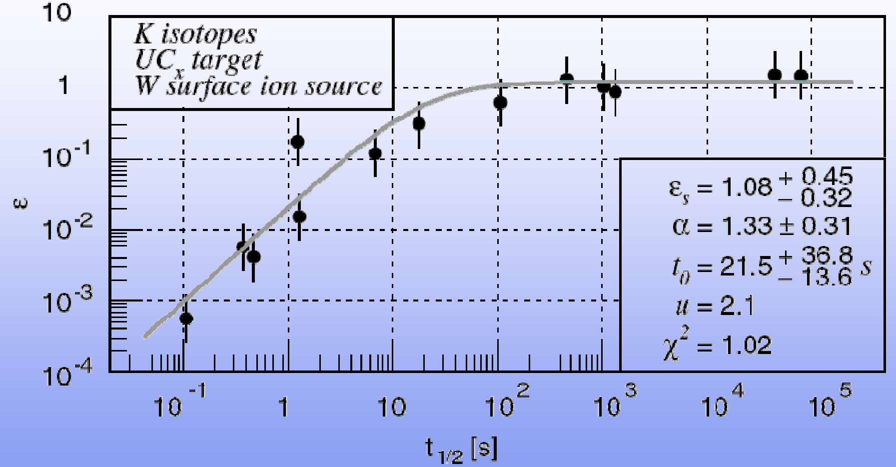
Rates: < 1pps

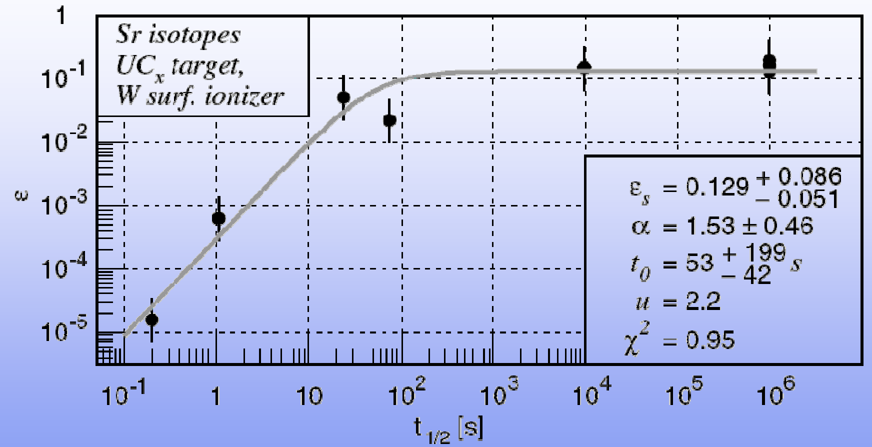
10 ($T_{1/2}$) - 1000 (BR) pps

At MYRRHA…..

Production rates à la K.-H. Schmidt et al.

- idea: release characteristics depend only on chemistry
  each isotope of same element has same release time,
  only decay half-life modulates this
- applies only to same target – element combination
- plot of ratio ε "measured rate / calculated rate" as function of half-life

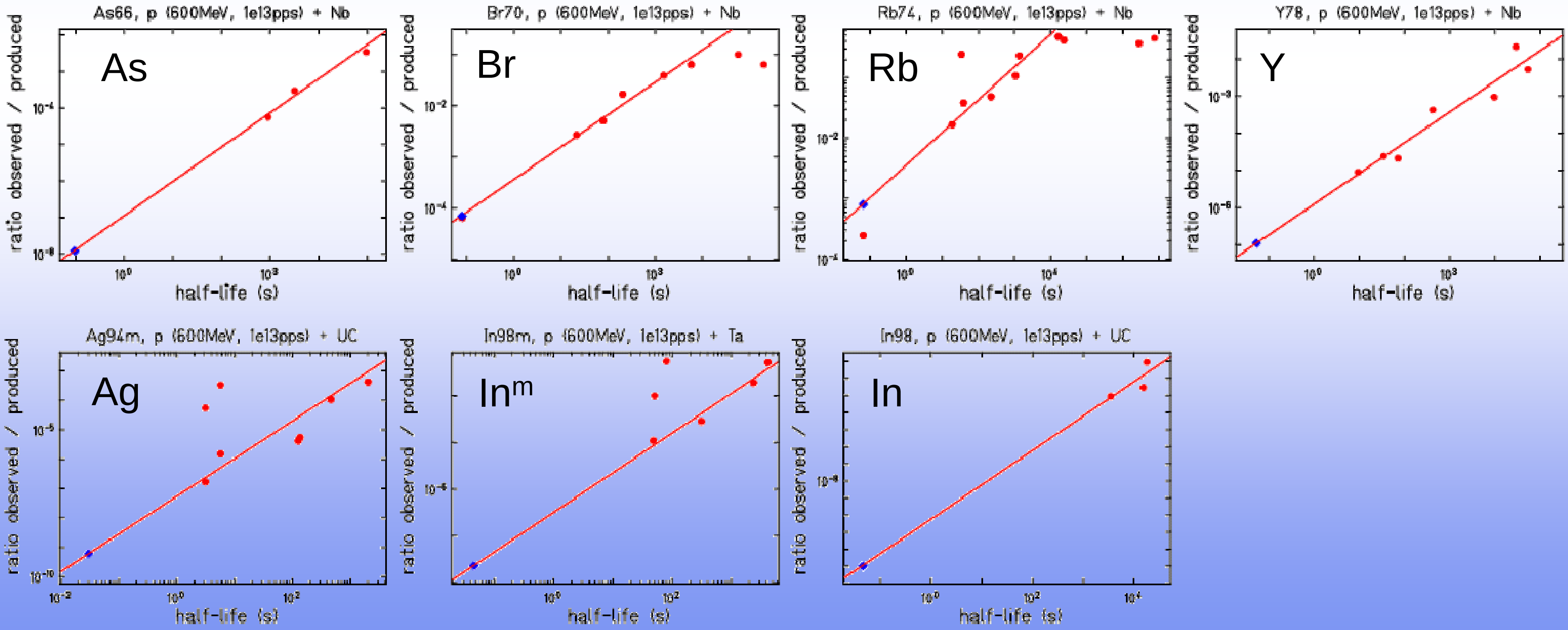




Rates estimates

- assumption: ISOLDE yields extrapolated as in Lukic et al., NIMA565 (2006) 784
- 600 MeV protons, 10^{13} pps
- targets of Nb, Ta, and UCx

➔ ➔ ➔ ➔ very rough estimates using EPAX2



ISOLDE Rates estimates

- ^{66}As: 0.4 pps
- ^{70}Br: 860 pps
- ^{74}Rb: 3300 pps
- ^{78}Y: 0.1 pps
- ^{94}Ag: 2e-8 (produced at GSI online separator with 2pps)
- ^{98}In: 2e-7

→→ → needs more detailed study…..

→ with a factor of 100 at MYRRHA

- number of counts needed: 10^7 for half-life measurement
- experiment time: 10 weeks
- assumption: 60000 s / day online (70%)
- half-life measurements: beam - on / beam - off loss: factor 5
- event rate needed: 10 pps
- does not take into account signal to background problems

Conclusion

• high precision measurements of 0+ to 0+ beta decay is topic of high current interest

• for the moment no facility to study the heaviest nuclei of interest

• some of them could be produced in reasonable amounts at MYRRHA

• elements can be produced with simple ion sources, especially surface ionisation source

• instrumentation needed is rather simple (except traps)

➔ ➔ ➔ ➔ necessity of long runs to get reasonable counting statistics